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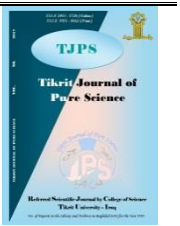

# Comparison Between the Properties of Three New Designs of Pinhole Magnetic Lens

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## ABSTRACT

Three different new designs of an objective pinhole lens were compared. Their magnetic and optical properties were studied using Finite Element Method for Calculating Magnetic Field Distribution (FEM-CMFD) and Magnetic Electron Lens Optical Properties (MELOP) software. The focal length ($f_o$), spherical aberration ($C_s$), chromatic aberration ($C_c$), and the resolving power ($\delta$) of each lens were compared at a range of relatively corrected acceleration voltages (Vr = 100 V-100 kV) and a constant excitation of (NI = 5280 A-t (where A represents Ampere and t represents turn)) and current density (2 A/mm$^2$) to find the best design. The L1 lens is similar to the Gemini lens. L2 and L3 are the traditional pinhole lens shape. The L1 lens gave the best results in terms of optical and magnetic properties as its optical properties at medium and low acceleration voltages. L2 and L3 Lenses had almost identical magnetic properties, but the difference was apparent in optical properties.

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# مقارنة بين خواص ثلاث تصاميم جديدة لعدسة الثقب المغناطيسية

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## الملخص

تم مقارنة ثلاث تصاميم جديدة لعدسة الثقب الشيئية، و تم دراسة خواصها المغناطيسية و البصرية بإستخدام برنامج طريقة العناصر المتناهية لحساب المجال المغناطيسي (FEM-CMFD) و برنامج الخصائص البصرية للعدسات الإلكترونية المغناطيسية (MELOPE)؛ حيث تم مقارنة البعد البؤري ($fo$)، و الزيغ الكروي ($C_s$)، و الزيغ اللوني ($C_c$)، و قدرة التحليل ($\delta$)، لكل عدسة عند مدى فولتية تعجيل مصححة نسبياً ($V_r$ = 10 V – 100 kV) وتهيج ثابت (NI = 5280 A-t) و كثافة تيار (2 A/mm$^2$) لإيجاد افضل تصميم. العدسة L1 شكلها قريب لعدسة Gemini. العدستان L2 وL3 هما الشكل التقليدي لعدسة الثقب. العدسة L1 حصلت على أفضل النتائج من حيث الخواص المغناطيسية و البصرية، حيث أعطت نتائج جيدة عند الجهود المنخفضة والمتوسطة. أما العدستان L2 و L3 فإن خواصهما المغناطيسية كانت متطابقة تقريباً و لكن الفرق واضح بينهما من حيث الخواص البصرية.

**الكلمات المفتاحية:** عدسة الثقب، بعد بؤري، زيغ كروي، زيغ لوني، قدرة التحليل.

## 1. Introduction

Electron optics science is only defined as the mathematical framework for calculating electron beam paths along electromagnetic fields, studying their behavior and controlling them. The term "optics" is used because magnetic and electrostatic lenses affect the electron beam like glass lenses on an optical beam [1]. There are three designs of objective lens: the first is called pinhole lens, where the specimens is outside the lens and its magnetic field. The second has specimen small (just several mm) to be placed inside the lens, which is called immersion lens. The third is a snorkel lens, where the specimen is outside the lens but inside its magnetic field [2].

In 2011, Al-Hujazie studied the design of a Gemini compound lens to correct chromatic aberration at low voltage [3]. In 2018, the researcher Al-Saleh studied a new design for a magnetic objective lens by comparing five designs and choosing the best design regarding optical and magnetic properties. The effect of bore diameter and electrode bore diameter was studied to improve the optical and magnetic properties of the proposed lenses [4]. In 2019, Al-Khashab and Al-Shamaa studied two models of magnetic objective lenses, Snorkel and Pinhole, using the Electron Optical Design (EOD) program. The Snorkel lens was chosen because it gives better results in terms of optical properties [2]. Zeina Aidan and Talib Mohsen studied 2021 a design for a double electromagnetic lens for a rotation and distortion display device. Using the EOD program, the lens consists of two identical lenses, where the focal characteristics of the lens were calculated in the two maximum magnification regions by changing the magnetic flux density in one of the two lenses by changing the diameter of the axial bore. The results showed the possibility of obtaining a double electromagnetic lens for the projector, and it has a minimum focal length [5]. In 2022, the researcher Ismail and others studied the effect of external pole geometry on the bipolar lens. Several innovative designs were designed for the bipolar lens, and the pole arm was changed with the current density. Focal length does not change [6]. In 2022, researchers Muhammad Al-Janaan and AL-Salih studied the possibility of improving the performance of a unipolar magnetic lens with different designs. Then, a study was conducted for each design that included studying the magnetization of the lens and calculating its magnetic field in addition to the magnetic flux density at three different current density values ($\sigma$ = 2,4 and 6 A/mm$^2$). The most evident values and behavior were obtained at ($\sigma$ = 2 A/mm$^2$) current density [7].

This work aims to design a new bipolar magnetic Pinhole lens and develop its optical properties to obtain the best design between suggested lenses.

## 2. Theoretical Part

The principle of the magnetic lenses depends on passing a continuous electric current D.C through an electric coil whose number of turns is (N), as it produces an axial magnetic field ($B_z$). This field affects the electrons within the path and deflects them towards the optical axis [8]. The magnetic field can be expressed according to Amper's law with the following relation:

$$\int_{-\infty}^{+\infty} \mathrm{B_z}\,(\mathrm{z})\mathrm{dz} = \mu_0 \mathrm{NI} \text{ ……………………………………..(1)}$$

Where (NI) is the lens excitation, measured by (Amper-turn), and the magnetic permeability in vacuum is ($\mu_0 = 4л\times10^{-7}$ H.m$^{-1}$). The axial ray equation can describe the motion of an electron within a magnetic field:

$$\frac{d^2r}{dz^2} + \left(\frac{e}{8mV_r}\right) {B_z}^2 r = 0 \text{ ……………………………………..(2)}$$

Where e is the electron's charge, m is the mass of the electron, r is the distance between the electron beam and the optical axis, and Vr is the relatively accelerated corrected voltage [9].

### 2.1 Computer Software

Lenses are designed by EOD program [10]. The program for calculating the Axil Magnetic Field Distribution of Magnetic Lenses uses the Finite Element Method (CMFD-FEM) [11]. The objective optical properties of the lenses were calculated by Magnetic Electron Lens Optical Properties (MELOP) [12].

## 3. Objective Pinhole Lens Design

Electronic, magnetic lens design requires choosing the lens electrodes' best shape. The appropriate shape and size of the coil and its operating conditions (the amount of excitation, relatively corrected acceleration voltage and the objective properties of the magnetic lens) [13].

Three pinhole lens designs were proposed. They were named L1, L2 and L3. The dimensions of the proposed lenses are represented by an axial length equal to (140 mm), a radial width of (75 mm), a rectangular file with an area of (1320 mm$^2$) and several turns (3000 turns) for all lenses, an air gap width (S = 4 mm), and an axial aperture diameter ($D_p$ = 2 mm) for L2 and L3. and ($D_p$ = 6 mm) for L1.

Figure (1) shows the proposed designs, their dimensions, and how the course and fine meshes are chosen. All proposed lenses have the same meshes on both vertical and horizontal axes to be in the same conditions.

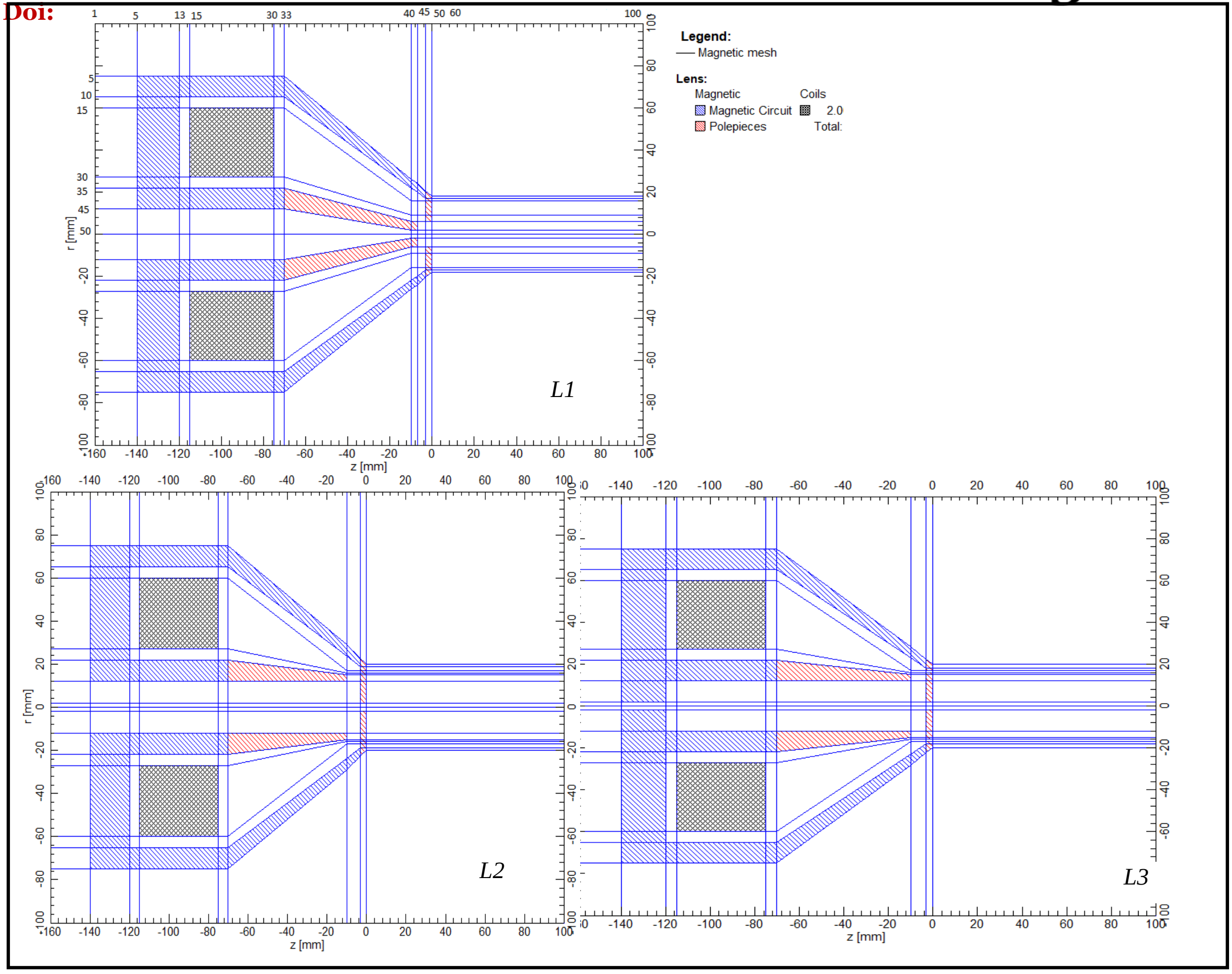

**Figure (1): Schematic diagram of three lenses with its meshes**

To design a magnetic lens with good efficiency, the lens should generate the highest axial magnetic flux density with the smallest half-width [14]. The magnetic flux density distribution of the three proposed pinhole lenses was calculated through the (FEM-CMFD) program based on the finite element method. Figure (2) shows the proposed lenses' axial magnetic flux density $B_z$.

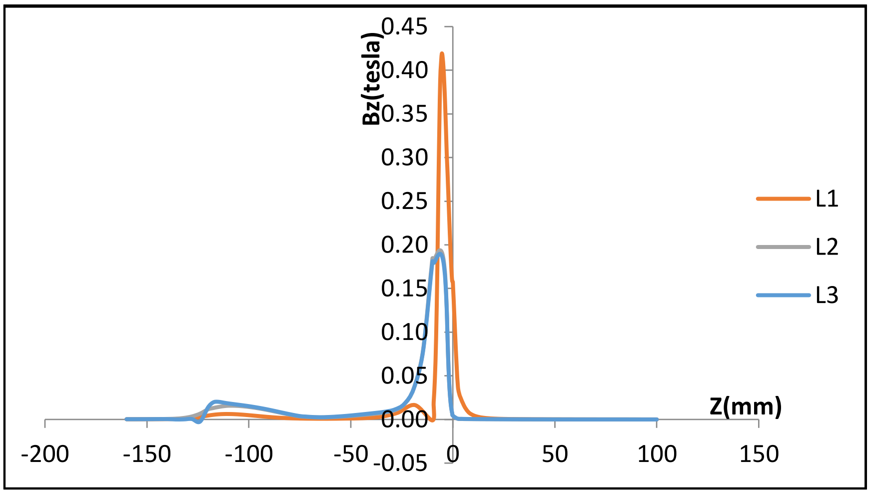

**Figure (2): Distribution of axial magnetic flux densit $B_z$ as a function of distance Z with excitation (NI = 5280 A-t), acceleration voltage (Vr = 10 kV), and current density (2A/mm$^2$)**

As shown in Table (1), the maximum value of the magnetic field intensity for the two lenses (L2 and L3) are very close, while L1 gave the best magnetic field, as the width of the half of the field is small. However, more is needed to assert that the optimal lens is L1, as there are other fundamental properties, such as the paths of the magnetic flux lines and the optical properties of the lenses, and they will be studied in detail in the subsequent items.

**Table (1): Summary of electromagnetic analyses for the three proposed lenses.**

| Lens | Pinpoint position Z(mm) | $B_z$ max(tesla) | Half-width (mm) |
|---|---|---|---|
| L1 | - 5.5 | 0.419031 | 7.8 |
| L2 | - 6.5 | 0.193699 | 15.027 |
| L3 | - 6.5 | 0.190654 | 15.43 |

## 4. Optical Properties

The optical properties are fundamental to knowing the optimal lens among the proposed lenses. The optical properties were studied using the MELOP program, where the lenses were tested at low and medium ranges of relatively corrected acceleration voltages (Vr = 100 V - 100 kV) and a fixed coil excitation of (NI = 5280 A-t) as previously mentioned. Figure (3) shows the focal length of the three proposed lenses as a function of voltage. It is clear from Figure (3) that lens L1 has the best focal length among the three lenses (lowest value) that one of the goals of this study is to obtain a pinhole lens with a small focal length among the other proposed lenses (L2 and L3). It was also noticed previously that the magnetic field was almost identical, while the focal length difference was slight. Figure (4) below shows a comparison of the spherical aberration of the three proposed lenses when (NI = 5280 A-t) is fixed and at a range of relatively corrected acceleration voltages of (Vr = 10 V- 100 kV). Figure (5) shows the chromatic aberration of three proposed lenses at a range of relatively corrected acceleration voltages (Vr = 100 V - 100 kV) and a constant excitation of (NI = 5280 A-t) and current density (2 A/mm$^2$).

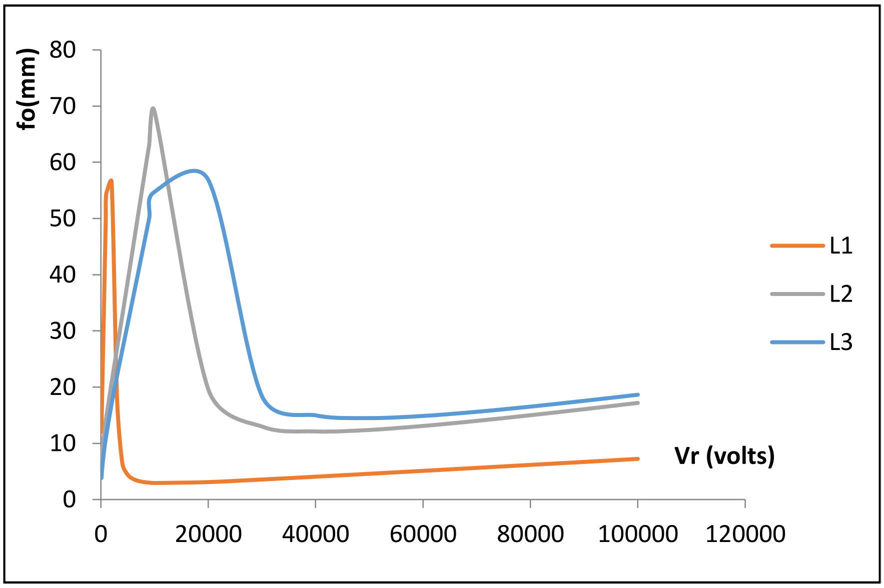

**Figure (3): Comparison of focal length as a function of voltages for the proposed pinhole lenses with (NI = 5280 A-t)**

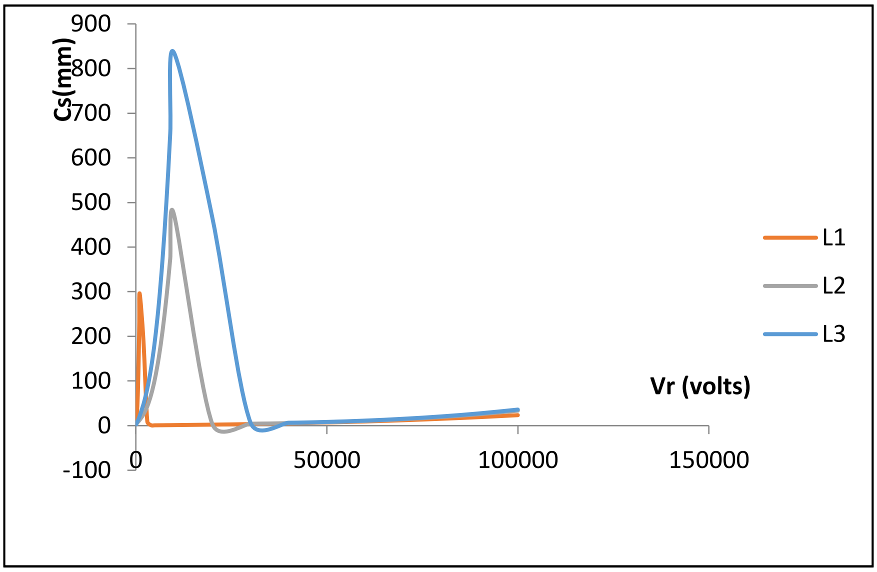

**Figure (4): Comparison between spherical aberration of the proposed pinhole lenses as a function of voltage at (NI = 5280 A-t)**

From Figure (4), lens L1 also gave the most minor spherical aberration among the three lenses at low voltages, followed by lens L2 and L3.

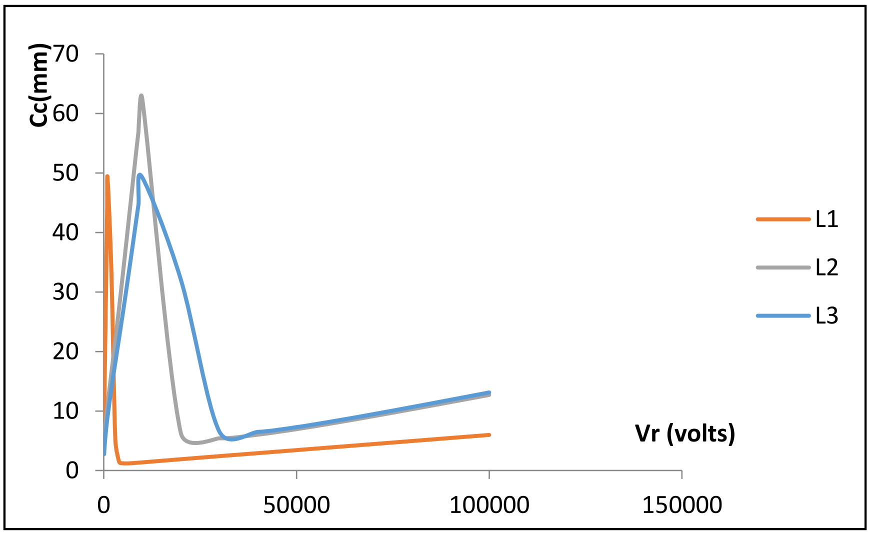

**Figure (5): Comparison between chromatic aberration of the proposed pinhole lenses as a function of voltage with a constant (NI = 5280 A-t)**

Although the L3 lens was the best in aberration and focal length, the resolving power of the three lenses was compared to choose the optimal lens among the proposed lenses in this work. Figure 6 shows this comparison.

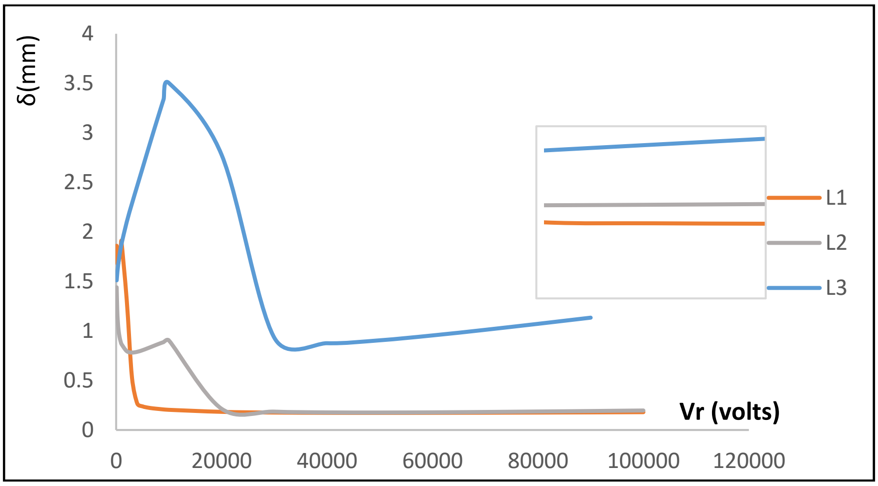

**Figure (6): Comparison between the proposed pinhole lenses' resolving power as a voltage function with a constant (NI = 5280 A-t)**

As shown in Figure (6), the L1 lens has the best analysis ability among the three lenses. The L1 lens gave the best results regarding magnetic and optical properties, which meets the goal of this research.

**Table (2): Comparison between the optical properties of three suggested lenses.**

| Lens | $V_r$ (kV) | $f_o$ (mm) | δ (nm) | $C_s$ (mm) | $C_c$ (mm) |
|---|---|---|---|---|---|
| L1 | 10 | 2.94 | 1.146529 | 1.22 | 1.36 |
|  | 20 | 3.1 | 1.030279 | 2.25 | 1.89 |
|  | 30 | 3.56 | 0.989716 | 3.52 | 2.41 |
| L2 | 10 | 68.98 | 5.086307 | 472.53 | 62.42 |
|  | 20 | 19.61 | 1.202827 | 4.18 | 6.3 |
|  | 30 | 12.99 | 1.04231 | 4.33 | 5.41 |
| L3 | 10 | 54.75 | 5.739209 | 835.28 | 49.23 |
|  | 20 | 56.86 | 3.910679 | 467.06 | 32.08 |
|  | 30 | 18.39 | 1.184839 | 7.23 | 6.53 |

A comparison was made of the three lenses for the optical properties and geometric dimensions of the three lenses, as shown in Table (2). The voltage range was chosen from (10 kV) to (30 kV) (NI = 5280 A-t). Table (2) shows that the L1 lens gives the best results regarding all optical properties. As for the L2 and L3 lenses, as we mentioned earlier, their magnetic field was almost identical.

## 5. Conclusions

This work compared three new pinhole lens designs regarding magnetic and optical properties. The lens with the best results from the proposed lenses (L1) is a lens whose shape tends to the Gemini lens, so it was considered a hybrid lens between the pinhole and Gemini lenses. L1 lens achieved good results in terms of optical and magnetic properties, as its optical properties at medium and low acceleration voltages were good. L2 and L3 lenses had almost identical magnetic properties, but the difference was apparent in optical properties. Lenses L2 and L3 did not achieve good results at medium and low voltages but improved slightly at (40,000 V).

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